



Beneficial effects of calcium chloride on glucose dehydration to 5-hydroxymethylfurfural in the presence of alumina as catalyst

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ABSTRACT

Aluminas with different acid-base properties (acid, neutral and basic) have been characterized by using XRD, N₂ sorption at –196 °C, XPS and NH₃-TPD, and tested for the dehydration of glucose to 5-hydroxymethylfurfural (HMF). Under the operating conditions used, the acid alumina showed the highest total acidity and the best catalytic performance, but the HMF yield hardly exceeded 20% since γ -Al₂O₃ apparently favored the secondary reactions. The presence of CaCl₂ in the reaction medium notably improved the catalytic performance, even at very short reaction times, due to the interaction between Ca²⁺ ions and glucose molecules, which favors the α -D-glucopyranose formation, thus enhancing glucose conversion and HMF yield up to 96% and 52%, respectively, at 175 °C after 15 min in presence of 0.65 g_{CaCl₂} · g_{aq.sol.}^{–1} and acid γ -Al₂O₃ as catalyst. The isomerization of glucose to fructose and subsequent dehydration to HMF does not seem to take place when CaCl₂ is present in the reaction medium, as inferred from ¹H NMR spectroscopy. Moreover, the catalyst was reused at least for three runs maintaining the catalytic activity, without an intermediate regeneration step.

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1. Introduction

Currently, the depletion of fossil fuel reserves, together with the unsteady price of crude oil and the environmental concerns due to global warming and pollution, are boosting the development of alternative and clean synthetic routes for producing chemicals and fuels from non-fossil carbon sources. Biomass is a very promising sustainable feedstock for this purpose since it is the only widely available and renewable carbon source [1–3]. Lignocellulosic biomass is the most abundant source of biomass with an estimated annual production about 2×10^{11} metric tons [4], and it is composed of three major components: cellulose (40–50%), hemicellulose (25–35%) and lignin (15–20%), and other extractable components, as small amounts of organic compounds [3,5]. Cellulose is a biopolymer consisting of D-glucose units linked via β -1,4-glycosidic bonds, being required a hydrolysis step to make

available glucose monomers. Thus, carbohydrates are the largest natural source of carbon, constituting up to 75% of the annual production of biomass and being a promising raw material with industrial applications in several areas of chemistry, food, paper and pharmaceutical industries [6]. However, the main drawback of carbohydrates as feedstock is the excess of oxygen of their molecular structures, which can be reduced by several chemical processes, as for example, their dehydration into a broad spectrum of important chemicals, such as furanic derivatives (furfural, 5-hydroxymethyl-furfural (HMF) or 2,5-furandicarboxylic acid) and levulinic acid [2]. HMF has been listed among the top 10 value-added bio-based chemical platforms by the US Department of Energy, due to its great potential as key intermediate to synthesize a wide range of value-added compounds currently derived from petroleum, as 2,5-furandicarboxylic acid, 5-hydroxymethylfuroic acid, 2,5-dimethylfuran, hydroxymethyl tetrahydrofurfural, 2,5-hydroxymethyl furan, 2,5-hydroxymethyl tetrahydrofuran, 5-ethoxymethylfurfural, levulinic acid, adipic acid, γ -valerolactone, caprolactam, caprolactone, among others [2,6–8]. Nevertheless, HMF is not yet produced at industrial scale

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in spite of its versatility and multifunctionality because of its high production cost. The HMF production is carried out by triple dehydration of C_6 carbohydrates in the presence of an acid catalyst. Although higher HMF selectivities are attained employing fructose as feedstock [9–14], glucose is preferred due to its abundance and availability. Mineral inorganic acids are traditionally used as acid catalysts, but they are corrosive and harmful for environment, in such a way that heterogeneous acid catalysts are preferred because they are environmentally friendly and human healthy, and they can be more easily separated and reused. In this sense, different solid acid catalysts have been tested for dehydration of glucose to HMF: cation exchange resins together with hydrotalcites [15], zeolites [16–18], sulfated zirconia [19,20], metal oxides such as TiO_2 [21–24], ZrO_2 [21–23,25], Nb_2O_5 [10,26], metal phosphates [27–29], among others.

On the other hand, aluminum oxides have been extensively employed as supports and catalysts, because they are abundant, cheap and hence commercially available, being $\gamma-Al_2O_3$ the most widely used. Thus, alumina has been utilized as such or in mixed oxides for dehydration of different sugars, such as glucose, fructose or xylose [30–35]. García-Sancho et al. [30] found that $\gamma-Al_2O_3$, used as support of Nb_2O_5 , increased conversion in xylose dehydration, although it favored secondary reactions, considerably decreasing the furfural selectivity. It is well known that a key factor in the HMF production, from glucose dehydration, is to minimize side reactions leading to HMF rehydration, producing levulinic and formic acids, as well as to the formation of humins and other soluble and insoluble polymers [2,6,36,37]. In order to increase the HMF yield, different strategies have been followed, as the use of biphasic systems, where the presence of an organic solvent allows the continuous extraction of HMF, immediately after its formation in the aqueous phase, minimizing side reactions and consequently improving HMF yield. Different solvents have been evaluated as extracting agents of HMF, such as toluene [38–40], tetrahydrofuran [39,41], 1-butanol [41,42], 2-butanol [10,43,44], acetone [45,46], diethyl ether [47,48] and mainly methyl isobutyl ketone [38,39,49–52].

Moreover, it has been reported the salting out effect improves the HMF selectivity increasing the partition coefficient, but the role of inorganic salts is not clear in the literature [42,53–55]. On the one hand, Marcotullio et al. [56,57] studied the influence of halide salts on dehydration of xylose to furfural, concluding that anions promoted the formation of an acyclic intermediate, 1,2-enediol, whose subsequent acid catalyzed dehydration led to furfural. However, Rasrendra et al. [58] compared halide and sulfate salts of different metals, pointing out that the anion effect was less important than the influence of cation. On the other hand, Román-Leshkov et al. [54] saturated the aqueous phase of a biphasic system with inorganic salts for dehydration of fructose to HMF, and concluded that the salting-out effect cannot be attributed to individual cationic or anionic contributions, being related to the interaction of all ionic species. Thus, the highest HMF selectivity was found by using K^+ and Na^+ cations maintaining constant the amount of Cl^- . Nevertheless, significant differences with respect to systems without salt were not found when the anion was changed from Cl^- to Br^- . The influence of alkali and alkaline earth metal salts on HMF production was also evaluated by Combs et al. [55], demonstrating that Ca^{2+} and Mg^{2+} accelerated the glucose decomposition rate via glucose complexation, since it had been previously demonstrated that the alkaline earth metal cations can form bidentate complexes by interacting with two oxygen atoms of glucose [59,60]. However, the reason why these cations favor the glucose decomposition has not been hitherto understood unequivocally.

In this work, the dehydration of glucose to HMF has been evaluated by using different mesoporous $\gamma-Al_2O_3$ with acid, neutral or basic character, in a biphasic water–MIBK solvent system to avoid

side reactions involving HMF. The addition of inorganic salts such as $NaCl$ and $CaCl_2$ in the reaction medium has been carried out in order to reach the maximum HMF yields. Likewise, the influence of $CaCl_2$ on the possible reaction pathways from 1H NMR results has been elucidated for the first time. Different parameters such as the reaction time, the amount of catalyst and its possible reuse, have been also studied.

2. Experimental

2.1. Reagents

Three different commercial aluminas (Alfa-Aesar, Brockmann Grade I, 58 Å) have been employed as solid acid catalysts for glucose dehydration to HMF: acid, neutral and basic alumina, which have been denoted as Al-x, where x = a, n and b indicate their acid, neutral or basic character, respectively.

For the catalytic tests, the following chemicals have been utilized: glucose (Sigma-Aldrich, >99%), fructose (Sigma-Aldrich, >99%), sodium chloride (VWR, 99%) and calcium chloride (VWR, 97%). Deionized water and methyl isobutyl ketone (MIBK, VWR, 98%) have been used as solvents.

2.2. Characterization of catalysts

Powder diffraction patterns were collected on an PANalytical automated diffractometer, EMPYREAN model, using $Cu-K\alpha$ -1,2 (1.5406 Å) radiation and a last generation PIXcel detector.

The textural parameters were determined from the nitrogen adsorption–desorption isotherms at $-196^\circ C$, obtained by using an automatic ASAP 2020 model of gas adsorption analyser from Micromeritics. Prior to N_2 adsorption, the samples were degassed at $200^\circ C$ and 10^{-4} mbar for 10 h. Surface areas were determined by using the Brunauer–Emmett–Teller (BET) equation and taking a value of 16.2 Å^2 for the cross section of the adsorbed nitrogen molecule at $-196^\circ C$. Pore size distributions were calculated with the BJH method.

X-ray photoelectron spectra were obtained with a Physical Electronics PHI 5700 spectrometer with non-monochromatic $Mg K\alpha$ radiation (300 W, 15 kV, and 1253.6 eV) with a multi-channel detector. Spectra were recorded in the constant pass energy mode at 29.35 eV, using a 720 μm diameter analysis area. Charge referencing was measured against adventitious carbon (C 1s at 284.8 eV). A PHI ACCESS ESCA-V6.0F software package was used for acquisition and data analysis. A Shirley-type background was subtracted from the signals. Recorded spectra were always fitted using Gaussian–Lorentzian curves in order to determine accurately the binding energies of the different element core levels.

The temperature-programmed desorption of ammonia (NH_3 -TPD) was carried out to evaluate the total surface acidity of catalysts. After cleaning of catalysts (80 mg) with helium up to $550^\circ C$ and subsequent adsorption of ammonia at $100^\circ C$, the NH_3 -TPD was performed by raising the temperature from 100 to $550^\circ C$, under a helium flow of 40 mL min^{-1} , with a heating rate of $10^\circ C \text{ min}^{-1}$ and maintained at $550^\circ C$ for 15 min. The evolved ammonia was analyzed by using a TCD detector of a gas chromatograph (Shimadzu GC-14A).

Thermogravimetric analyses (TGA) were performed with a TGA/DSC 1 model (Mettler-Toledo), under air flow of 50 mL min^{-1} with a heating ramp of $10^\circ C \text{ min}^{-1}$, from room temperature until $900^\circ C$. The carbon content of spent catalysts was measured with a LECO CHNS 932 analyser.

2.3. Catalytic tests

Glucose dehydration catalytic tests were performed in batch at 175 °C, by using a glass pressure tube with thread bushing (Ace, 15 mL, pressure rated to 10 bar) and magnetic stirring. In a typical experiment, 150 mg of glucose, 50 mg of catalyst, 1.5 mL of deionized water and 3.5 mL of methyl isobutyl ketone (MIBK) were poured into the reactor. Prior the experiments, reactors were always purged with nitrogen to avoid side reactions of HMF which decrease its yield. The reaction mixture was heated with a thermostatically controlled oil bath. The reaction was quenched by submerging the reactor in a cool water bath; the liquid phases were separated, filtered and the analysis of products was performed in both phases by high performance liquid chromatography (HPLC), being glucose, fructose and HMF the only detected products. A JASCO instrument equipped with quaternary gradient pump (PU-2089), multiwavelength detector (MD-2015), autosampler (AS-2055), column oven (co-2065) using a Phenomenex Luna C18 reversed-phase column (250 mm × 4.6 mm, 5 μm) and Phenomenex Rezex RCM-Monosaccharide Ca²⁺ (8%) (300 mm × 7.8 mm, 5 μm), was employed. Both glucose and fructose were monitored using a refractive index detector for aqueous phase, while HMF production was monitored using a UV detector in both phases. The mobile phases consisted in pure methanol (flow rate 0.5 mL min⁻¹) for Luna C18 and deionized water (flow rate 0.6 mL min⁻¹) for Rezex RCM-Monosaccharide, being the columns at room temperature and 80 °C, respectively.

3. Results and discussion

One of the main drawbacks in the production of HMF from glucose dehydration is related to the formation of by-products, such as humins and soluble/insoluble polymers, as well as levulinic and formic acids coming from rehydration processes, which decreases the HMF yield and provokes the catalyst deactivation. In order to minimize these side reactions, the use of organic co-solvents has been largely reported in the literature, being methyl isobutyl ketone one of most often used [39,49,52]. In this work, a biphasic water-MIBK system has been employed to study the dehydration of glucose to HMF.

Firstly, the influence of the acid-base character of alumina on the catalytic performance for dehydration of glucose has been evaluated at 175 °C, by using a glucose/catalyst weight ratio of 3 (Fig. 1). The Al-x catalysts display similar structural and textural properties, since the existence of γ -Al₂O₃ (2 θ = 37.71, 45.87 and 66.89°, JCPDS No 01-074-2206) is detected in all cases by XRD (Fig. S1 of Supplementary information) and similar values of BET surface areas (137–158 m² g⁻¹), pore volumes (0.236–0.252 cm³ g⁻¹) and pore size distributions are found (Table S1 and Fig. S2). However, significant differences are detected in the catalytic behavior which may be due to their different values of total acidity calculated by NH₃-TPD (Table S1 and Fig. S3). Thus, the acid alumina shows the highest glucose conversion and HMF yield, as expected considering its high total acidity (478 μmole NH₃·g_{cat}⁻¹), with a glucose conversion increasing from 50%, after only 15 min of reaction, until 83% after 90 min. On the contrary, the basic alumina does not exceed 55% of glucose conversion, even after 120 min, which is due to its lower acidity (232 μmole NH₃·g_{cat}⁻¹). The neutral alumina exhibits an intermediate behavior in the same manner of its total acidity (401 μmole NH₃·g_{cat}⁻¹). Moreover, the pH of alumina suspension in the reaction medium decreases when the catalyst acidity raises, achieving values of 4.5, 6.4 and 8.9 for Al-a, Al-n and Al-b, respectively. This low pH could be explained by the deprotonation of the strong acid groups present on the catalyst surface, forming hydronium ions in aqueous solution, which provokes a pH decrease.

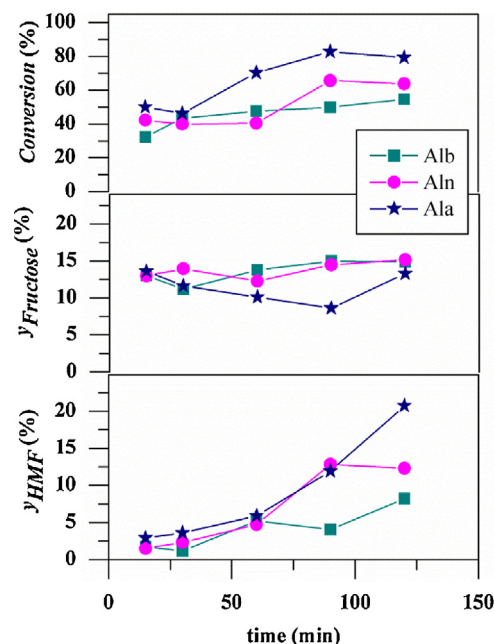


Fig. 1. Glucose conversion, fructose and HMF yields as a function of reaction time at 175 °C for Al-x catalysts (glucose/catalyst weight ratio of 3).

The study of the homogeneous contribution was performed by adjusting the pH to 4.5 by using H₂SO₄, obtaining a glucose conversion, after 1 h at 175 °C, lower (32%) than that attained in presence of Al-a. It is clear that these hydronium ions contribute to the dehydration process, but the absence of aluminum species in solution rules out the leaching of the solid catalyst and hence the participation of homogeneous catalysis to the overall catalytic activity.

Although all catalysts possess acid sites with a broad range of strength, as inferred from the different desorption temperatures of ammonia [61], a higher amount of stronger acid sites is detected for acid and neutral alumina, which in turn show better catalytic performances. On the other hand, small amounts of sodium and chlorine have been detected by XPS in these catalysts (Table 1), in such a way that the acid and basic aluminas display the highest Cl and Na content, respectively, which may be due to the alumina washing with HCl and NaOH to provide acid or basic character, as previously pointed out by Nassar et al. [62]. In addition, the binding energy (BE) values found for Al 2p_{3/2} and O 1s in Al-x catalysts are characteristic of γ -Al₂O₃ [63–65]. The surface Al/O atomic ratio is similar in all cases (0.454–0.471), but lower than the theoretical atomic ratio (0.666), which could be explained by the presence of surface hydroxyl groups.

Nevertheless, the values of HMF yield are not too high, in spite of the high glucose conversion attained in the presence of Al-x catalysts, being lower than 21%, even in the case of the most active catalyst, Al-a (Fig. 1). This fact may be due to Al₂O₃ favors secondary reactions, as already observed in the dehydration of other carbohydrates like xylose [30], consequently decreasing the HMF yield. Therefore, it is essential the development of alternative strategies to reduce the side reactions and improve the catalytic performance of these mesoporous aluminas. Considering that the Al-a catalyst has demonstrated to be the most active catalyst, this has been chosen to optimize other reaction parameters. In this context, the dehydration of glucose in presence of inorganic salts has been studied as a strategy to inhibit side reactions.

Recently, different authors have reported the favorable influence of adding inorganic salts on HMF production [53–55]. Likewise, furfural yield in dehydration of xylose was successfully improved by using sodium chloride, achieving a maximum yield

Table 1
XPS parameters of alumina catalysts.

Sample	Binding Energy (eV)		Atomic Concentration (%)			Atomic Ratio
	Al 2p _{3/2}	O 1s	Na	Cl	Ca	
Al-a	73.7	530.7	0.45	1.74	–	0.464
Al-n	73.5	530.4	0.24	0.71	–	0.454
Al-b	73.8	530.7	0.73	0	–	0.471
RAI-a	73.7	531.3 (93.5%) 532.7 (6.5%)	–	0.07	0.08	0.114

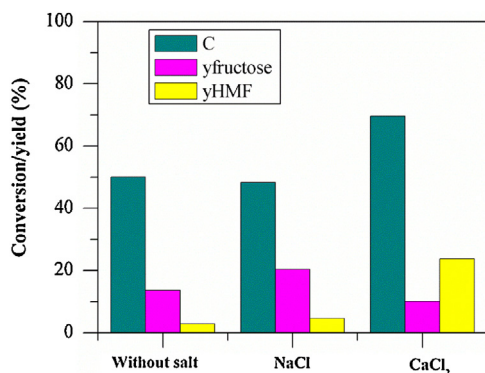


Fig. 2. Influence of adding NaCl ($0.2 \text{ g} \cdot \text{g}_{\text{aq.sol.}}^{-1}$) or CaCl_2 ($0.386 \text{ g} \cdot \text{g}_{\text{aq.sol.}}^{-1}$) on glucose conversion, fructose and HMF yields for Al-a catalyst at 175°C after 15 min (glucose/catalyst weight ratio of 3).

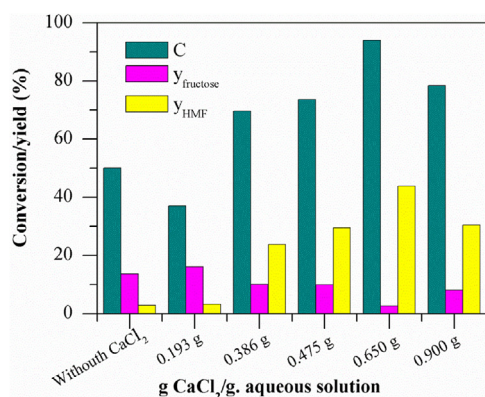


Fig. 3. Effect of CaCl_2 addition on glucose conversion, fructose and HMF yields for Al-a catalyst at 175°C after 15 min (glucose/catalyst weight ratio of 3).

with $0.2 \text{ g} \cdot \text{g}_{\text{aq.sol.}}^{-1}$ [66]. Thus, in the present work, this same concentration of NaCl has been utilized for dehydration of glucose to favor HMF production, as well as another salt, CaCl_2 , to compare the effect of the addition of different salts by using a similar molar concentration of salt (Fig. 2). The presence of NaCl barely modifies the catalytic performance under the selected reaction conditions, since a slight increase of HMF yield is only observed. However, calcium chloride improves both glucose conversion and HMF yield, so the amount of this salt in the reaction medium has been optimized.

Thus, in order to improve the HMF selectivity in presence of Al-a catalyst, the influence of the addition of different calcium chloride concentrations has been studied at short reaction times to minimize secondary reactions (Fig. 3). According to these results, the higher CaCl_2 concentrations are employed, the higher values of glucose conversion and HMF yield are achieved, being maximum with $0.65 \text{ g} \cdot \text{g}_{\text{aq.sol.}}^{-1}$ per g aqueous solution, which increases the conversion and HMF yield from 50% and 3%, in absence of salt, up to 94% and 44% with CaCl_2 , respectively. However, the catalytic results get

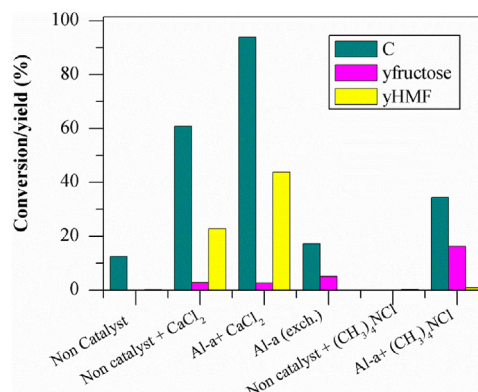


Fig. 4. Comparison between non-catalytic and catalytic processes in presence of CaCl_2 or $(\text{CH}_3)_4\text{NCl}$ and catalytic behavior of Al-a(exch.) (175°C , 15 min and glucose/Al-a weight ratio of 3).

worse when the amount of calcium chloride is near to the saturation value ($0.9 \text{ g} \cdot \text{g}_{\text{aq.sol.}}^{-1}$). It should be noted that the CaCl_2 addition considerably promotes the HMF production even after only 15 min of reaction, and it improves the catalytic behavior of acid alumina. In order to deepen about the effect of calcium chloride, the partition coefficients, R (defined as the ratio of HMF concentrations in the organic and aqueous phases), have been determined. A positive effect is found, in such a way that it increases when CaCl_2 is employed ($R = 1.2$ – 1.8) with respect to the catalytic test in absence of salt ($R = 1.01$). However, there is not a clear trend, since the R value rises when lower CaCl_2 concentrations are used ($R = 1.8$ for $0.386 \text{ g} \cdot \text{g}_{\text{aq.sol.}}^{-1}$) but it decreases for the highest concentrations of salt, being $R = 1.2$ for $0.65 \text{ g} \cdot \text{g}_{\text{aq.sol.}}^{-1}$. Moreover, a similar partition coefficient ($R = 1.8$) has been found for NaCl and CaCl_2 for reaction conditions used in Fig. 2, in spite of the presence of NaCl does not improve the catalytic performance. Therefore, the dependency of the HMF yield on the CaCl_2 concentration cannot be explained only by the raise of partition coefficient, since the maximum conversion and HMF yield values are not attained for the highest R values.

On the other hand, the results obtained in presence of Al-a as acid catalyst by using CaCl_2 have been compared with the non-catalyzed process (in the absence of catalyst), without and with salt (Fig. 4). Negligible values of glucose conversion and HMF yield (12% and 0.2%, respectively) are obtained for the non-catalyzed process in absence of CaCl_2 (at 175°C and 15 min). However, the glucose conversion and HMF yield rise up to 61% and 23%, respectively, in presence of $0.65 \text{ g} \cdot \text{g}_{\text{aq.sol.}}^{-1}$, even in absence of catalyst, which demonstrates that this salt plays a key role during the reaction. Combs et al. [55] reported that salts modify the ionic strength, thus affecting the activity coefficient of the solution, decreasing the effective pH and facilitating the glucose dehydration. In order to confirm that the salting-out effect is not due to the total ionic strength in the reaction medium, another salt with the same anion, $(\text{CH}_3)_4\text{N}^+ \text{Cl}^-$, has been studied (Fig. 4) by using the same ionic

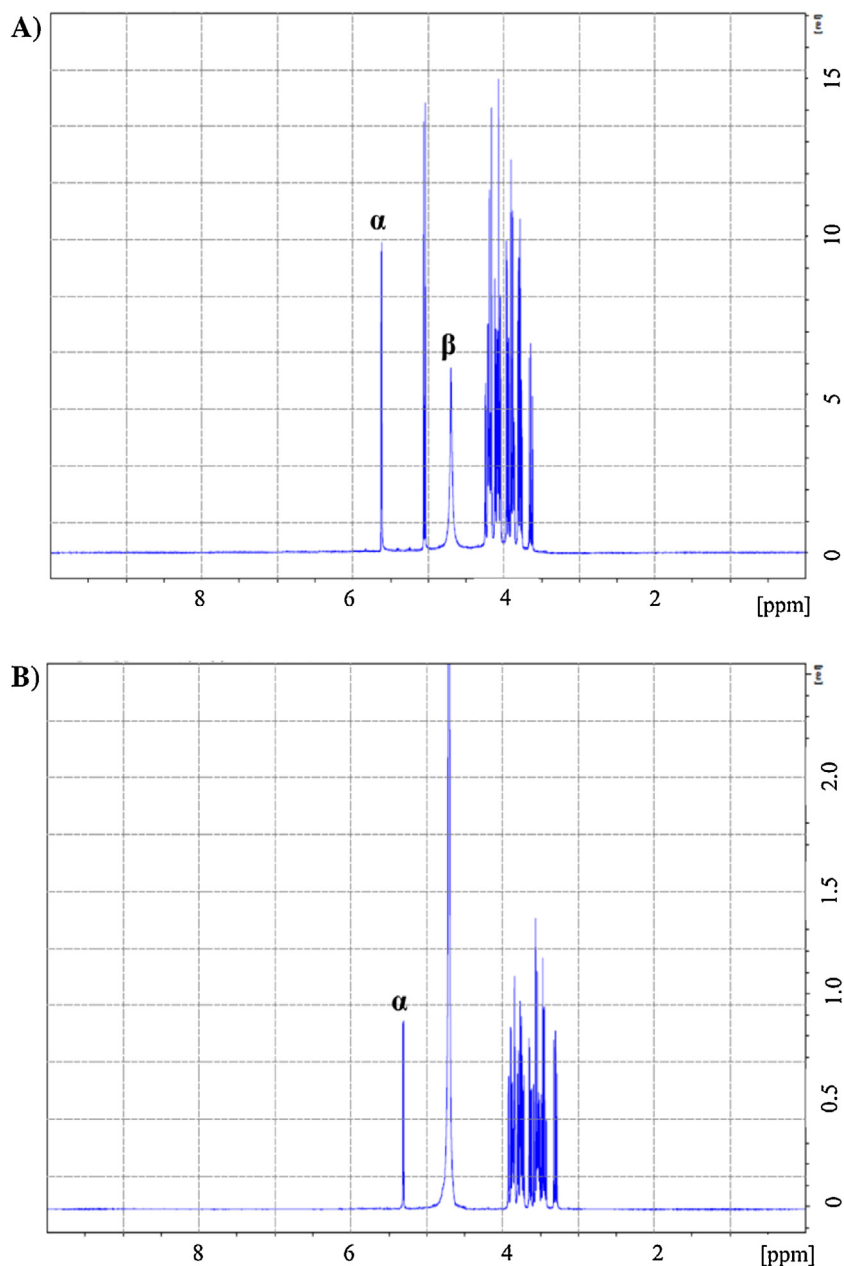


Fig. 5. ^1H NMR spectra of glucose in D_2O (A) before and (B) after addition of CaCl_2 .

strength. Unlike CaCl_2 , none activity is detected for non-catalyzed system. Moreover, insignificant amelioration of the catalytic performance is reached when the Al-a catalyst is incorporated in the presence of tetramethylammonium chloride, even achieving lower values than Al-a by itself. Some authors have proposed that halide anions promote the formation of 1,2-enediol, which favors the subsequent dehydration steps of carbohydrates [56,57]. However, a clear correlation between the presence of chloride anions and the enhancement of catalytic performance has not been found in the present work since the use of other halide salts as NaCl or $(\text{CH}_3)_4\text{NCl}$ provide worse results than CaCl_2 . These results agree well with Rasrendra et al. [58] who reported that anion effects have less importance for glucose conversion than cation effects, and Wu et al. [67] who found that chloride salts did not significantly accelerate the decomposition rate of glucose or improve the HMF selectiv-

ity. Therefore, it seems clear that calcium cations play a key role in dehydration of glucose to HMF.

In order to rule out that the improvement of catalytic performance in presence of calcium cations could be due to the incorporation of these cations to alumina, the Al-a catalyst was treated with a CaCl_2 solution ($0.65 \text{ gCaCl}_2 \cdot \text{g}_{\text{aq.sol}}^{-1}$) under the reaction conditions (175°C and 15 min) without glucose in the medium. Afterwards, this catalyst denoted as Al-a(exch.) was recovered, dried and put in contact with the reaction mixture (150 mg of glucose, 1.5 mL of deionized water without CaCl_2 and 3.5 mL of MIBK). Thus, it could be verified whether cation exchange happens on catalyst surface and it is responsible for increasing glucose conversion and HMF yield. The presence of calcium has been detected by XPS (0.06%), but the Al-a(exch.) catalyst barely improves the non-catalyzed process (Fig. 4), attaining to worse results than those achieved with the Al-a catalyst. Therefore, it could be affirmed that

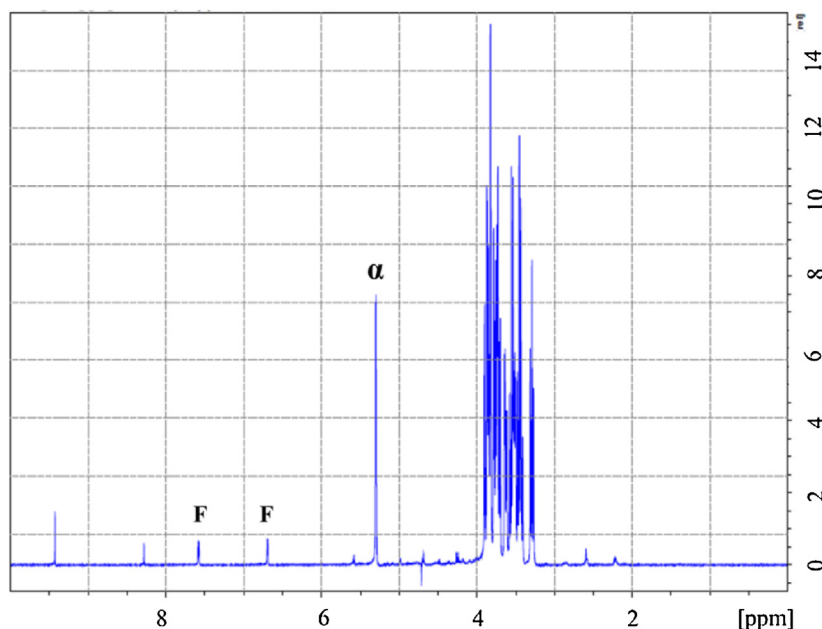


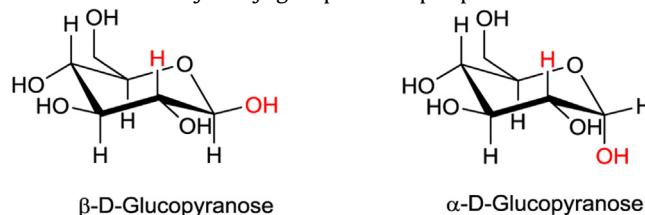
Fig. 6. ^1H NMR spectra of a solution of glucose and CaCl_2 in D_2O , after 24 h at 115°C .

the promising catalytic results in presence of Ca^{2+} are not due to the interaction between these cations and catalyst. Indeed, it is noticeable that the acid alumina is almost inactive when it is previously treated with calcium chloride, so this treatment provokes the neutralization of available acid sites.

Therefore, it seems that CaCl_2 directly participates in dehydration of glucose to HMF. Combs et al. [55] previously found that the presence of alkaline earth metal salts accelerates glucose decomposition rates via glucose complexation with salts. They also observed that Ca^{2+} was more selective than Mg^{2+} towards HMF, which gives rise to higher amounts of levulinic acid. Nevertheless, they attained glucose conversion and HMF yield values, for all salts studied by employing HCl as catalyst, much lower than those reported in the present work, achieving a HMF yield of only 3.8% after 60 min at 160°C , by adding CaCl_2 to the solution. It is well known that alkaline earth cations can form bidentate complexes with different saccharides or even cellulose [59,60,68,69]. Although the formation of reasonably stable calcium complexes with cyclic sugar requires the presence of three hydroxyl groups in an axial-equatorial-axial sequence in the molecule, other cyclic sugars without this sequence as D-glucose can form weaker Ca^{2+} complexes. Pallagi et al. [70] reported that the complexing with cations causes a downfield shift of the signals of some protons in the ^1H NMR spectra, but no substantial changes in the NMR spectra of glucose were detected in spite of the formation of these complexes is plausible. The binding of D-glucose to these metal cations occurs through its α -anomeric configuration [71] and the equilibrium between α and β forms is shifted toward the formation of the α form in the presence of metallic cation [70]. Therefore, it would be possible that the formation of these complexes directly participates in the conversion of glucose to HMF [55]. Similarly, Song et al. [68] reported that Ca^{2+} forms complexes with two oxygen atoms more easily than Na^+ which agrees with Pallagi et al. [70] who found that complexation with sodium cations can be considered negligible compared to calcium ones. This fact would explain why NaCl does not improve the catalytic performance as opposed to CaCl_2 .

These assumptions have been verified by using ^1H NMR spectroscopy. A D-glucose solution in D_2O shows the characteristic α/β proportion of both anomeric situations of the pyranosyl chair dis-

position at room temperature (Fig. 5A). Normally, β -glucopyranose is favored over α form in aqueous medium [72,73]. However, the addition of CaCl_2 to this solution induces the total displacement of the β form towards the α conformer, as evidences the spectrum of Fig. 5B. On the β -D-glucopyranosyl anomer, none of the adjacent H and OH groups on the pyranose ring are on the antiperiplanar conformation. However, on the α -D-glucopyranosyl anomer, the C2-H and the anomeric hydroxyl group are antiperiplanar.



The displacement of the equilibria of α/β conformer towards the α conformation points towards this preferring conformation for the catalytic transformation. It should be noted that in absence of Al_2O_3 , the reaction is slow, but however, on heating the D-glucose/ CaCl_2 complex (or mixture) in a sealed NMR tube at 115°C for 24 h, signals due to the furan ring of HMF are observed in the crude reaction mixture (Fig. 6). Thus, it could be inferred a cooperative contribution of both CaCl_2 and Al_2O_3 in the dehydration process: while alumina is the key catalytic compound involved in the D-glucose- hydroxymethylfurfural transformation, CaCl_2 acts providing the correct anomer for processing to take place efficiently.

The reaction mechanism of glucose dehydration to obtain HMF is not still clear in bibliography. Most of proposed mechanistic pathways involve fructose, both cyclic and linear forms, in such a way that glucose is isomerized to fructose that is subsequently dehydrated to HMF [74–77]. The glucose isomerization can be catalyzed by Lewis acid sites [27,78–80], so $\gamma\text{-Al}_2\text{O}_3$ would be an excellent candidate for this reaction. However, it can be observed in Fig. 4 that fructose yields obtained for non-catalyzed and catalyzed by Al-a processes, in presence of CaCl_2 , are low and very similar, even without Lewis catalyst, so the presence of this catalyst does not seem to favor the fructose formation when calcium cations are in the reaction medium. Moreover, the ^1H NMR spectrum after heat-

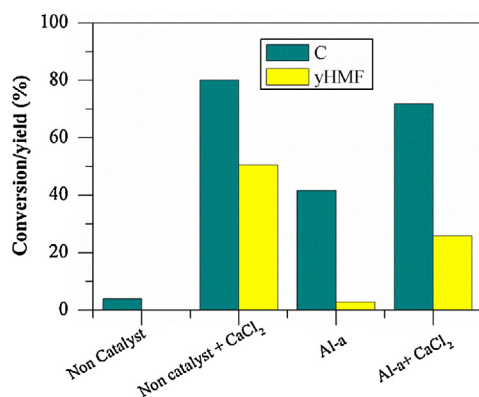


Fig. 7. Influence of CaCl₂ and Al-a catalyst on fructose conversion and HMF yield (175 °C, 15 min and fructose/catalyst weight ratio of 3).

ing of D-glucose in presence of CaCl₂ at 115 °C for 24 h reveals signals associated to the furan ring, but fructose signals are not detected (Fig. 6). Therefore, it would be interesting to study HMF formation from fructose in presence of alumina and/or calcium chloride, but considering that Román-Leshkov et al. [54] previously studied the influence of CaCl₂ on fructose dehydration and negligible changes were observed, since the conversion was maintained and the HMF selectivity only increased from 69%, without salt, up to 73% in its presence. Hence, the dehydration of fructose under similar experimental conditions has been evaluated (Fig. 7). Both fructose conversion and HMF yield considerably increase in presence of calcium chloride, even without catalyst, achieving values of 80% and 51% respectively, being possible that calcium cations also interact with fructose molecules. However, the amount of non-converted fructose after dehydration in presence of CaCl₂ (20%) is proportionally higher than the unreacted fructose after glucose dehydration (<3%) under similar experimental conditions, so both reactions seem to follow different pathways. Indeed, the catalytic results get worse when Al-a is employed together with CaCl₂ for fructose dehydration. Nevertheless, the presence of acid alumina considerably enhanced HMF yield from glucose dehydration with respect to the non-catalyzed process, as previously shown in Fig. 4. Therefore, it seems plausible to affirm that glucose dehydration into HMF in presence of calcium cations does not occur through the isomerization to fructose and subsequent dehydration. Indeed, Qian [81] proposed a route for fructose formation from HMF as intermediate that could explain this fructose concentration.

On the other hand, it has been checked that the presence of CaCl₂ in the reaction medium favors the formation of α anomer that leads to more efficient dehydration, so the anomeric site would be implied in dehydration. Nonetheless, some authors have reported that the HMF production from the protonation of anomeric site is unlikely [72,74], although it is certain that these studies were realized in presence of Brønsted acid sites. It seems clear that there is a correlation between the increase of α -D-glucopyranose due to the presence of CaCl₂ in the reaction medium and the considerable increase of HMF yield.

Moreover, the influence of the catalyst concentration on the catalytic performance has been also evaluated by varying the glucose:catalyst weight ratio from 10:1 to 1:1 (Fig. 8) and using 0.65 gCaCl₂·g_{aq.sol.}⁻¹. It can be observed that glucose conversion is higher than 90% in all cases, achieving up to 98% when a glucose:catalyst weight ratio of 1:1 is employed. However, a trend related to the amount of catalyst is not detected. With regard to the HMF yield, a decrease is produced when higher amounts of catalyst are used, being maximum (52%) for a glucose:catalyst weight ratio equal to 6:1. Therefore, although it is necessary the use of Al-a to ameliorate both glucose conversion and HMF yield in the presence

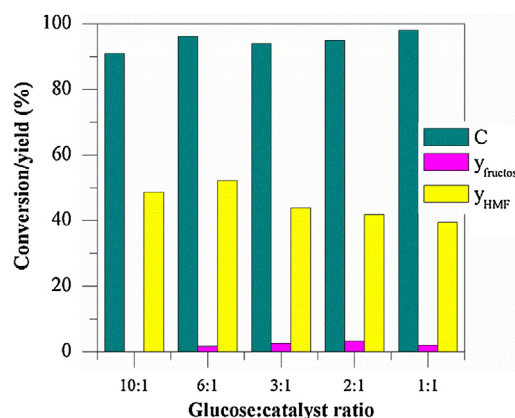


Fig. 8. Glucose conversion, fructose and HMF yield as function of glucose:catalyst weight ratio for Al-a catalyst at 175 °C and 15 min in presence of 0.65 gCaCl₂·g_{aq.sol.}⁻¹.

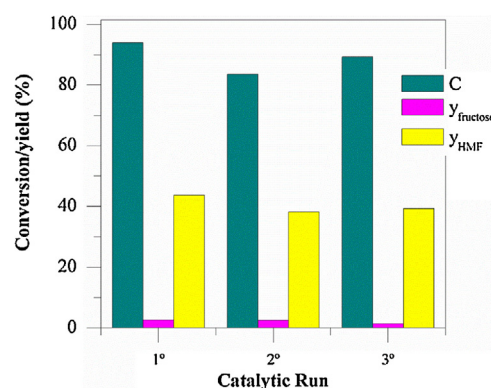


Fig. 9. Reutilization study for the Al-a catalyst at 175 °C after 15 min in the presence of 0.65 gCaCl₂·g_{aq.sol.}⁻¹ (glucose/catalyst weight ratio of 3).

of CaCl₂ (Fig. 4), the glucose:catalyst weight ratio must be between 10:1 and 6:1, possibly due to the fact that a higher alumina loading could favor side reactions, thus decreasing the HMF yield, as it has been previously mentioned.

The reuse of Al-a has been also evaluated, at 175 °C for 15 min, in the presence of 0.65 gCaCl₂·g_{aq.sol.}⁻¹, with a glucose:catalyst weight ratio of 3 over three consecutive catalytic runs (Fig. 9). Although it has been demonstrated that a glucose:catalyst weight ratio of 6:1 provides higher HMF yields, a larger amount of catalyst has been employed in these recycling experiments to minimize losses of catalyst from manipulation after each run. The catalyst remained inside the reactor, without any treatment, after each run and a new reaction mixture (glucose, CaCl₂, water and MIBK) was added to perform the reaction under similar experimental conditions. The catalyst maintains its activity after three catalytic runs in such a way that conversion and HMF yield values only decrease from 94% and 44% until 89% and 39%, respectively, after the third catalytic run. Therefore, the Al-a catalyst can be reused without any regeneration step to remove possible organic deposits on the catalyst surface.

Finally, the spent Al-a catalyst (RAI-a) has been recovered after reaction at 175 °C and 15 min, in the presence of 0.65 gCaCl₂·g_{aq.sol.}⁻¹, and characterized by several techniques. Thus, the presence of humins, which are responsible of HMF losses, has been confirmed by CHN analysis, since a carbon content of 8.3% has been found. Likewise, a high carbon content (66.53%) has been detected by XPS, corroborating that the slight catalytic deactivation may be associated to surface carbonaceous deposits. It should be noted that the atomic Al/O ratio decreases with respect to fresh catalyst due to carbonaceous solids are preferably deposited over Al atoms (Table 1). However, no significant differences for values of BE of Al

2p_{3/2} and O 1s have been observed between the fresh and spent catalysts with the exception of a new band at 532.7 eV in the O 1s region, which can be attributed to C–O bonds of some adsorbed molecules. Moreover, a small amount of calcium is detected by XPS on the catalyst surface after reaction. On the other hand, although the Al-a catalyst is active at least for three catalytic runs, the presence of humins could decrease the effectiveness of catalyst along cycles, so its regeneration would be necessary. Hence, the thermal stability of humin deposits has been studied by TGA under air (Fig. S4), in such a way that the catalyst could be regenerated by thermal treatment between 500 and 600 °C, thus allowing the calcination of carbonaceous deposits.

4. Conclusions

Different mesoporous aluminas with similar textural properties have demonstrated to be active in glucose dehydration into 5-hydroxymethylfurfural, being a key factor its total acidity, since the acid alumina provided better catalytic results than basic and neutral ones. The addition of different inorganic salts, such as NaCl and CaCl₂, in order to decrease side reactions has been compared, being much more effective calcium chloride, reaching values of glucose conversion and HMF yield of 96% and 52%, respectively, at 175 °C after 15 min in presence of 0.65 gCaCl₂ · g_{aq.sol.}^{−1}, by using a glucose/γ-Al₂O₃ weight ratio of 6. The presence of calcium cations shifts the α/β equilibrium towards the α conformation of glucose, as inferred from ¹H NMR results, which could favor its dehydration into HMF, demonstrating a synergistic effect between CaCl₂ and acid γ-Al₂O₃ that provides interesting HMF yields at very short reaction times (15 min). The glucose dehydration to HMF seems not to proceed predominantly via initial isomerization to fructose when CaCl₂ is in the reaction medium. In spite of carbonaceous deposits after reaction, the acid alumina can be reused in presence of CaCl₂ at least for three catalytic runs without any regeneration step.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.apcatb.2017.01.065>.

References

- [1] M. Stocker, *Angew. Chem. Int. Ed.* 47 (2008) 9200–9211.
- [2] R. van Putten, J. van der Waal, E. de Jong, C. Rasrendra, H. Heeres, J. de Vries, *Chem. Rev.* 113 (2013) 1499–1597.
- [3] D. Alonso, J. Bond, J. Dumesic, *Green Chem.* 12 (2010) 1493–1513.
- [4] T. Wang, M. Nolte, B. Shanks, *Green Chem.* 16 (2014) 548–572.
- [5] V. Menon, M. Rao, *Prog. Energy Combust.* 38 (2012) 522–550.
- [6] M. Zakrzewska, E. Bogel-Lukasik, R. Bogel-Lukasik, *Chem. Rev.* 111 (2011) 397–417.
- [7] S. Teong, G. Yi, Y. Zhang, *Green Chem.* 16 (2014) 2015–2026.
- [8] J. Bozell, G. Petersen, *Green Chem.* 12 (2010) 539–554.
- [9] X. Qi, M. Watanabe, T. Aida, R. Smith, *Green Chem.* 10 (2008) 799–805.
- [10] F. Yang, Q. Liu, X. Bai, Y. Du, *Bioresour. Technol.* 102 (2011) 3424–3429.
- [11] T. Armaroli, G. Busca, C. Carlini, M. Giuttari, A. Galletti, G. Sbrana, *J. Mol. Catal. A-Chem.* 151 (2000) 233–243.
- [12] P. Svilen, J. Coelho, C. Afonso, *ChemSusChem* 5 (2012) 1388–1391.
- [13] C. Fan, H. Guan, H. Zhang, J. Wang, S. Wang, X. Wang, *Biomass Bioenergy* 35 (2011) 2659–2665.
- [14] Q. Zhao, L. Wang, S. Zhao, X. Wang, S. Wang, *Fuel* 90 (2011) 2289–2293.
- [15] A. Takagaki, M. Ohara, S. Nishimura, K. Ebitani, *Chem. Commun.* (2009) 6276–6278.
- [16] K. Lourvanij, G. Rorrer, *Ind. Eng. Chem. Res.* 32 (1993) 11–19.
- [17] K. Lourvanij, G. Rorrer, *J. Chem. Technol. Biotechnol.* 69 (1997) 35–44.
- [18] L. Hu, Z. Wu, J. Xu, Y. Sun, L. Lin, S. Liu, *J. Chem. Eng.* 244 (2014) 137–144.
- [19] J. Zhang, S. Wu, H. Zhang, B. Li, *Bioresources* 7 (2012) 3984–3998.
- [20] Y. Yang, X. Xiang, D. Tong, C. Hu, M. Abu-Omar, *Bioresour. Technol.* 116 (2012) 302–306.
- [21] M. Watanabe, Y. Aizawa, T. Iida, R. Nishimura, H. Inomata, *Appl. Catal. A-Gen.* 295 (2005) 150–156.
- [22] X. Qi, M. Watanabe, T. Aida, R. Smith, *Catal. Commun.* 9 (2008) 2244–2249.
- [23] A. Chareonlimkun, V. Champreda, A. Shotipruk, N. Laosiripojana, *Fuel* 89 (2010) 2873–2880.
- [24] A. Chareonlimkun, V. Champreda, A. Shotipruk, N. Laosiripojana, *Bioresour. Technol.* 101 (2010) 4179–4186.
- [25] X. Qi, M. Watanabe, T. Aida, R. Smith, *Bioresour. Technol.* 109 (2012) 224–228.
- [26] K. Nakajima, Y. Baba, R. Noma, M. Kitano, J. Kondo, S. Hayashi, M. Hara, *J. Am. Chem. Soc.* 133 (2011) 4224–4227.
- [27] V. Ordonsky, J. van der Schaaf, J. Schouten, T. Nijhuis, *ChemSusChem* 6 (2013) 1697–1707.
- [28] V. Ordonsky, V. Sushkevich, J. Schouten, J. van der Schaaf, T. Nijhuis, *J. Catal.* 300 (2013) 37–46.
- [29] R. Weingarten, Y. Kim, G. Tompsett, A. Fernandez, K. Han, E. Hagaman, W. Conner, J. Dumesic, G. Huber, *J. Catal.* 304 (2013) 123–134.
- [30] C. García-Sancho, I. Agirrezabal-Telleria, M. Guemez, P. Maireles-Torres, *Appl. Catal. B-Environ.* 152 (2014) 1–10.
- [31] C. Song, H. Liu, Y. Li, S. Ge, H. Wang, W. Zhu, Y. Chang, C. Han, H. Li, *Chin. J. Chem.* 32 (2014) 434–442.
- [32] J. Kruger, V. Choudhary, V. Nikolakis, D. Vlachos, *ACS Catal.* 3 (2013) 1279–1291.
- [33] W. Zeng, D. Cheng, F. Chen, X. Zhan, *Catal. Lett.* 133 (2009) 221–226.
- [34] S. You, N. Park, E. Park, M. Park, *J. Ind. Eng. Chem.* 21 (2015) 350–355.
- [35] S. You, Y. Kim, E. Park, *Reac. Kinet. Mech. Catal.* 111 (2014) 521–534.
- [36] C. Moreau, R. Durand, S. Razigade, J. Duhamet, P. Faugetas, P. Rivalier, P. Ros, G. Avignon, *Appl. Catal. A-Gen.* 145 (1996) 211–224.
- [37] A. Ranoux, K. Djanashvili, I. Arends, U. Hanefeld, *ACS Catal.* 3 (2013) 760–763.
- [38] S. Lima, P. Neves, M. Antunes, M. Pillinger, N. Ignatyev, A. Valente, *Appl. Catal. A-Gen.* 363 (2009) 93–99.
- [39] J. Chan, Y. Zhang, *ChemSusChem* 2 (2009) 731–734.
- [40] S. Lima, M. Antunes, A. Fernandes, M. Pillinger, M. Ribeiro, A. Valente, *Molecules* 15 (2010) 3863–3877.
- [41] E. Nikolla, Y. Roman-Leshkov, M. Moliner, M. Davis, *ACS Catal.* 1 (2011) 408–410.
- [42] Y. Roman-Leshkov, C. Barrett, Z. Liu, J. Dumesic, *Nature* 447 (2007) 982–986.
- [43] Y. Roman-Leshkov, J. Chheda, J. Dumesic, *Science* 312 (2006) 1933–1937.
- [44] F. Yang, Q. Liu, M. Yue, X. Bai, Y. Du, *Chem. Commun.* 47 (2011) 4469–4471.
- [45] X. Qi, M. Watanabe, T. Aida, R. Smith, *Ind. Eng. Chem. Res.* 47 (2008) 9234–9239.
- [46] Y. Zhang, H. Du, X. Qian, E. Chen, *Energy Fuel* 24 (2010) 2410–2417.
- [47] G. Yong, Y. Zhang, J. Ying, *Angew. Chem. Int. Ed.* 47 (2008) 9345–9348.
- [48] C. Moreau, A. Finiels, L. Vanoye, *J. Mol. Catal. A-Chem.* 253 (2006) 165–169.
- [49] J. Chheda, Y. Roman-Leshkov, J. Dumesic, *Green Chem.* 9 (2007) 342–350.
- [50] S. De, S. Dutta, B. Saha, *Green Chem.* 13 (2011) 2859–2868.
- [51] L. Rigal, A. Gaset, *Biomass* 3 (1983) 151–163.
- [52] C. McNeff, D. Nowlan, L. McNeff, B. Yan, R. Fedie, *Appl. Catal. A-Gen.* 384 (2010) 65–69.
- [53] C. Rasrendra, J. Soetedjo, I. Makertihartha, S. Adisasmito, H. Heeres, *Top. Catal.* 55 (2012) 543–549.
- [54] Y. Roman-Leshkov, J. Dumesic, *Top. Catal.* 52 (2009) 297–303.
- [55] E. Combs, B. Cinlar, Y. Pagan-Torres, J. Dumesic, B. Shanks, *Catal. Commun.* 30 (2013) 1–4.
- [56] G. Marcotullio, W. De Jong, *Green Chem.* 12 (2010) 1739–1746.
- [57] G. Marcotullio, W. de Jong, *Carbohydr. Res.* 346 (2011) 1291–1293.
- [58] C. Rasrendra, I. Makertihartha, S. Adisasmito, H. Heeres, *Top. Catal.* 53 (2010) 1241–1247.
- [59] C. Yang, X. Lu, W. Lin, X. Yang, J. Yao, *Chem. Res. Chin. U* 22 (2006) 524–532.
- [60] S. Tyrlik, D. Szerszen, M. Olejnik, W. Danikiewicz, *J. Mol. Catal. A-Chem.* 106 (1996) 223–233.
- [61] P. Berteau, B. Delmon, A. Crucq, A. Frennet, *Catal. Today* 5 (1989) 121–137.
- [62] N. Nassar, A. Hassan, P. Pereira-Almao, *J. Colloid Interface Sci.* 360 (2011) 233–238.
- [63] C.D. Wagner, J.F. Moulder, L.E. Davis, W.M. Riggs, *Handbook of X-ray Photoelectron Spectroscopy*, 1979.
- [64] C. Wagner, D. Passoja, H. Hillery, T. Kinisky, H. Six, W. Jansen, J. Taylor, *J. Vac. Sci. Technol.* 21 (1982) 933–944.
- [65] T. Barr, *J. Vac. Sci. Technol. A* 9 (1991) 1793–1805.
- [66] C. García-Sancho, I. Sadaba, R. Moreno-Tost, J. Merida-Robles, J. Santamaria-Gonzalez, M. Lopez-Granados, P. Maireles-Torres, *ChemSusChem* 6 (2013) 635–642.
- [67] X. Wu, J. Fu, X. Lu, *Bioresour. Technol.* 119 (2012) 48–54.
- [68] J. Song, H. Fan, J. Ma, B. Han, *Green Chem.* 15 (2013) 2619–2635.
- [69] H. Tajmir-Riahi, J. Inorg. Biochem. 27 (1986) 123–131.

- [70] A. Pallagi, C. Dudas, Z. Csendes, P. Forgo, I. Palinko, P. Sipos, J. Mol. Struct. 993 (2011) 336–340.
- [71] H. Tajmir-Riahi, Carbohydr. Res. 183 (1988) 35–46.
- [72] X. Lin, Y. Qu, Y. Lv, Y. Xi, D. Phillips, C. Liu, Phys. Chem. Chem. Phys. 15 (2013) 2967–2982.
- [73] A. Kosaka, M. Aida, Y. Katsumoto, J. Mol. Struct. 1093 (2015) 195–200.
- [74] G. Yang, E. Pidko, E. Hensen, J. Catal. 295 (2012) 122–132.
- [75] E. Pidko, V. Degirmenci, E. Hensen, ChemCatChem 4 (2012) 1263–1271.
- [76] A. Amarasekara, A. Razzaq, Carbohydr. Res. 386 (2014) 86–91.
- [77] Y. Pagan-Torres, T. Wang, J. Gallo, B. Shanks, J. Dumesic, ACS Catal. 2 (2012) 930–934.
- [78] I. Agirrezabal-Telleria, I. Gandarias, P. Arias, Catal. Today 234 (2014) 42–58.
- [79] P. Zhou, Z. Zhang, Catal. Sci. Technol. 6 (2016) 3694–3712.
- [80] T.D. Swift, H. Nguyen, Z. Erdman, J.S. Kruger, V. Nikolakis, D.G. Vlachos, J. Catal. 333 (2016) 149–161.
- [81] X. Qian, Top. Catal. 55 (2012) 218–226.